

# A Search for Millisecond Pulsars in *Fermi* LAT-Detected Globular Clusters

Megan E. DeCesar

Department of Astronomy, University of Maryland, College Park, MD 20740, USA

Scott M. Ransom

National Radio Astronomy Observatory, Charlottesville, VA 22903, USA

Paul S. Ray

U.S. Naval Research Laboratory, Washington, D.C. 20375, USA

We have searched for millisecond pulsars (MSPs) in two globular clusters detected by the *Fermi* Large Area Telescope. These clusters contained no known MSPs prior to their detections in  $\gamma$ -rays. The discovery of  $\gamma$ -ray emission from many MSPs and the prevalence of MSPs in globular clusters points to a population of MSPs as the likely source of the detected GeV emission, directing our search for new cluster MSPs. We observed NGC 6652 and NGC 6388 at 2 GHz with the Green Bank Ultimate Pulsar Processing Instrument pulsar backend at the Green Bank Telescope using the coherent dedispersion mode. We have discovered one MSP in the  $\gamma$ -ray error circle of NGC 6652. This pulsar is interesting because, while positionally coincident with the GC, it has a much lower dispersion measure than expected from the NE2001 galactic free electron density model. It is unclear whether the MSP is a foreground pulsar or a cluster member, and whether the pulsar, cluster, or both, is responsible for the  $\gamma$ -ray emission. Timing the MSP will give the pulsar position and a solid identification of the pulsar as a cluster member if it is within a few core radii of the cluster center, as well as the opportunity to search for  $\gamma$ -ray pulsations and determine the origin of the GeV emission.

## 1. INTRODUCTION

Globular clusters (GCs) contain orders of magnitude more low-mass X-ray binaries (LMXBs) and recycled millisecond pulsars (MSPs) per unit mass than the Galactic disk [7]. The high stellar densities in GCs lead to high probabilities for stellar interactions in these systems, through which binaries form and subsequently evolve. GCs are the most likely hosts of exotic binary systems, like MSP-main sequence binaries, highly eccentric binaries [17], and MSP-black hole binaries, which would not form via normal stellar evolution in the disk. Additionally, one can learn about cluster dynamics and gas content, as well as MSP formation and evolution (due to the high statistics), through the study of cluster pulsars.

The *Fermi* Gamma-ray Space Telescope Large Area Telescope (LAT) [6] has detected 18 previously known field MSPs at energies  $> 100$  MeV. Like normal pulsars [4], all display a spectrum consistent with an exponentially cutoff power law, with cutoff energy  $E_c \sim \text{few GeV}$  [2]. Radio searches of unidentified *Fermi* sources with pulsar-like spectra have led to recent discoveries of 35 new MSPs (e.g. [18]).

While individual  $\gamma$ -ray MSPs would only be detectable in nearby GCs or under special circumstances, a whole population of MSPs is detectable at typical GC distances by the LAT [20]. Fifteen GCs have been detected by the LAT thus far [12] [3] [19] [5], and those with the largest number of known MSPs, 47 Tucanae [1] and Terzan 5, are the brightest of all clusters detected at GeV energies. About half the GCs have spectra consistent with that of an ensemble of MSPs [20].

Nine of the LAT-detected GCs contain no known MSPs. As the LAT has provided targets to search for MSPs in the field, we expect it is pointing us to clusters that host MSPs but have remained undetected. Many of these clusters are quite distant, of order 10 kpc away, and/or are located farther south than is accessible by the Green Bank and Arecibo telescopes, whose sensitivities are required to detect MSPs at such distances. We chose to search for MSPs in two clusters, NGC 6388 and NGC 6652, with the Green Bank Ultimate Pulsar Processing Instrument (GUPPI) pulsar backend at the Green Bank Telescope (GBT). GUPPI is  $\sim$ twice as sensitive as SPIGOT, the previous pulsar backend at the GBT, so may provide the extra sensitivity needed to detect pulsars that were not detectable in past searches.

## 2. TARGETED CLUSTERS

The clusters we searched, NGC 6388 and NGC 6652, were chosen primarily because of their high significance at GeV energies. They are very distant, at  $\sim 11.6$  and 9 kpc respectively [3]. The dispersion measures (DM) of NGC 6388 and NGC 6652 are respectively  $\text{DM} \sim 345$  and  $196 \text{ cm}^{-3} \text{ pc}$ , according to the NE2001 model of galactic free electrons [8]. Typical predicted errors on the NE2001 DM estimates are up to  $\sim 50\%$  for individual sources, though in some cases the error can be larger (up to  $\gtrsim 100\%$ ). At such large DMs, scattering is significant, and searching at a moderately high frequency with coherent de-dispersion is the best recipe to reduce scattering.

The GeV emission coincident with NGC 6388 has

a hard power law spectrum ( $\Gamma \sim 1.1$ ) with a clear cutoff at  $\sim 1.8$  GeV [3], consistent with the combined spectrum from an ensemble of  $\gamma$ -ray MSPs [20]. This cluster is the most compact GC known [10], and therefore has the highest stellar encounter rate. Chandra observations show  $\sim 60$  sources within its half-mass radius, many of which are LMXBs [14]. It is therefore expected that many MSPs reside in this cluster, and only its distance has prevented their detection.

NGC 6652 is firmly detected by the LAT, but no spectral cutoff was measured by [3]. Its power law spectrum is hard, with a photon index  $\sim 1$ . While this cluster is not very compact, it contains 3 faint X-ray sources and a LMXB [11], suggesting that MSPs likely exist in this cluster.

### 3. OBSERVATIONS AND SEARCHES

We observed both GCs at S-band (2 GHz) with the GUPPI backend on the GBT between 2010 Oct 19 and 2011 May 6. The data have 800 MHz bandwidth and  $40.96 \mu\text{s}$  time resolution. The observations were performed in coherent search mode (e.g. [13]), in which the incoming data are dedispersed in real time at a pre-determined DM to minimize pulse broadening. Each of the 2048 frequency channels across the 800 MHz of bandwidth were coherently dedispersed at the predicted DMs for the clusters. The channels were then combined in a standard incoherent summation over a wide variety of search DMs. As the coherent dedispersion search mode on GUPPI has only been available for the past few years, these are some of the first coherent searches that have been attempted.

These clusters are located at low declinations, and between observatory scheduling constraints and the physical constraints of the telescope, it was possible to observe them for only  $\leq 3$  hr. NGC 6388 was observed 8 times, with individual observations lasting between 1.5 and 2.5 hr. NGC 6652 was observed 6 times for 2–3 hr each. The integration times limit our sensitivity to  $\sim 20 \mu\text{Jy}$  for NGC 6388 and  $\sim 18 \mu\text{Jy}$  for NGC 6652, for the longest observations.

All datasets, except one short observation of each cluster, have been searched at the time of writing. The full data sets were processed with PRESTO [15], which we used to dedisperse the time series at  $\sim 5000$  DMs between 0 and  $800 \text{ cm}^{-3} \text{ pc}$  and to perform acceleration searches [16] required to detect most MSPs in binary orbits. We searched the full integrations with the acceleration search parameter  $z_{\text{max}} = 200$ . Additional searches of shorter integration times and higher  $z_{\text{max}}$  values are underway.

### 4. DISCOVERY OF A MSP COINCIDENT WITH NGC 6652

Out of these searches has come the discovery of one new MSP thus far, PSR J1839–3259. The discovery plot of this new pulsar is shown in Figure 1. The pulsar period is  $\sim 3.89$  ms, and is clearly accelerated; initial timing efforts suggest an orbital period of 1–2 days. Out of 6 observations, in only one is it not detected, perhaps due to an eclipse.

This pulsar’s DM is  $63.35 \text{ cm}^{-3} \text{ pc}$ , much lower than the  $196 \text{ cm}^{-3} \text{ pc}$  predicted in NE2001 [8]. This leads us to question its association with NGC 6652. Judging from a *SkyView*<sup>1</sup> image, the cluster’s angular diameter appears to be  $\sim 2.2$  arcmin. The GBT beam at S-band is  $\sim 6$  arcmin. A chance coincidence between the cluster field and pulsar location is therefore possible. The NE2001 model can be very inaccurate, especially in the direction of the galactic center where the cluster is located, so it is also possible that the expected DM is very different from the true value. A discovery of a second pulsar at the same DM would clinch the MSP as lying inside the cluster, but searches at and around this DM for other pulsars have so far been unsuccessful. Timing the MSP will reveal its true location, as the phase-connected timing solution will include a very accurate position that can be compared with the coordinates of the cluster core. In addition, if it is in the cluster, there is a  $\sim 50\%$  chance that it will have a negative period derivative due to the cluster potential.

The new radio MSP may also be a new  $\gamma$ -ray pulsar. The LAT 95% error radius of NGC 6652 is 7.2 arcmin, larger than the angular size of the cluster and the S-band beam, so if the MSP is not in NGC 6652, it could be a few arcminutes from the cluster and still be coincident with the cluster location at GeV energies. Upcoming observations will allow us to obtain a timing solution, with which we will fold the LAT photons to search for  $\gamma$ -ray pulsations. If found, we will look in the off-peak phases to determine if any emission from NGC 6652 remains. If there is no remaining emission from NGC 6652, then the pulsar is either in the foreground and the origin of the  $\gamma$ -rays, or it is a cluster member but solely responsible for the emission seen by the LAT, as in [9].

### 5. CONCLUSIONS

The *Fermi* LAT has led the way to the discoveries of many new radio MSPs through pointed observations of unidentified  $\gamma$ -ray sources. Following this lead, we

<sup>1</sup><http://skyview.gsfc.nasa.gov>

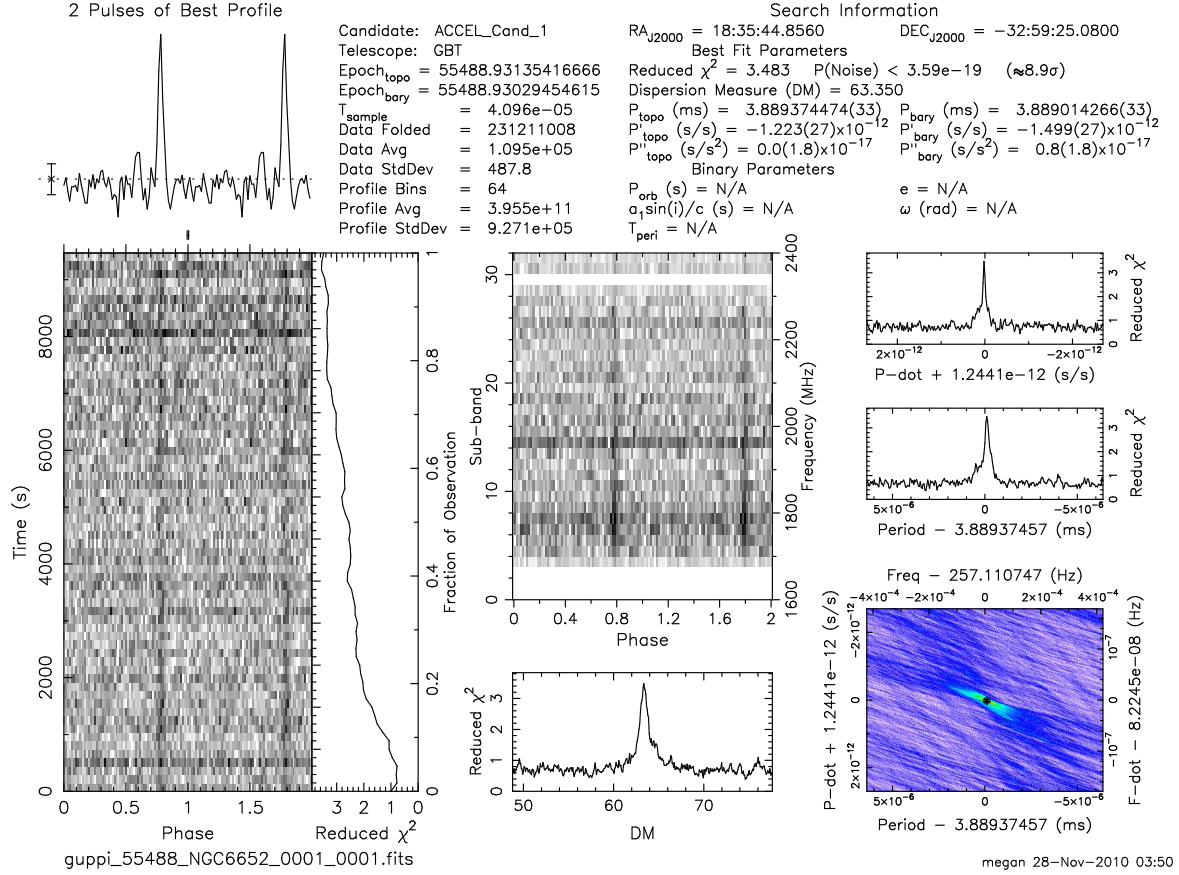


Figure 1: The PRESTO discovery plot of PSR J1839–3259. Two cycles of the pulse profile integrated over time and frequency are shown in the upper left. The bottom left plot shows the persistence of the pulsar in time, while the middle plot shows the same across the bandwidth. The pulse signal-to-noise peaks in DM at  $63.35 \text{ cm}^{-3} \text{ pc}$ , shown in the bottom middle plot. The peak in  $\chi^2$  at the pulsar spin period and period derivative are shown in the plots on the right. The period derivative measured here is not the intrinsic  $\dot{P}$  of the pulsar, but rather reflects the orbital acceleration of the pulsar during the observation.

searched for MSPs in two LAT-detected globular clusters with the Green Bank Telescope, with the expectation that each hosts a population of recycled pulsars.

We have discovered a new MSP coincident with the location of NGC 6652. PSR J1839–3259 has a low DM of  $63.35 \text{ cm}^{-3} \text{ pc}$ , much lower than the NE2001 expectation of nearly  $200 \text{ cm}^{-3} \text{ pc}$ , calling into question its true association with NGC 6652. A timing campaign of this pulsar will reveal whether or not it is a cluster member, and also if it is a  $\gamma$ -ray pulsar or if the  $\gamma$ -rays are primarily from the GC.

No cluster MSPs have conclusively been discovered from these observations thus far. While we have found many pulsar candidates near the expected DM values for the two GCs we searched, none repeat from one observation to the next, which is essential for confirming a pulsar detection. Scintillation is not an issue at such large distances and does not explain the lack of detections. The scattering timescale for NGC 6652 is  $\tau_{\text{scatt}} \sim 0.7 \mu\text{s}$ , and  $\tau_{\text{scatt}} \sim 3 \mu\text{s}$  for NGC 6388 [8]. These numbers change very little when the DM is dou-

bled to account for potential errors in the NE2001 model, so scattering probably does not play a role in our findings. It is most likely that the distances to the clusters, combined with the relatively short integration times due to their low declinations, are limiting our sensitivity to the MSPs that undoubtedly reside in these systems. Further observations and reprocessing of the data with higher acceleration searches may still yield detections of MSPs from these clusters. Additionally, several more clusters with no known MSPs have recently been detected by the LAT [19]. We will continue our search for cluster MSPs with the GBT in these newly  $\gamma$ -ray-detected globular clusters.

## Acknowledgments

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated

under cooperative agreement by Associated Universities, Inc.

The *Fermi* LAT Collaboration acknowledges support from a number of agencies and institutes for both development and the operation of the LAT as well as scientific data analysis. These include NASA and DOE in the United States, CEA/Irfu and IN2P3/CNRS in France, ASI and INFN in Italy, MEXT, KEK, and JAXA in Japan, and the K. A. Wallenberg Foundation, the Swedish Research Council and the National Space Board in Sweden. Additional support from INAF in Italy and CNES in France for science analysis during the operations phase is also gratefully acknowledged.

The authors thank F. Camilo at Columbia University for the use of his computer cluster.

MED acknowledges Eliza Jolene Bailey, whose birth coincided with the first observation of NGC 6652 that led to the detection of PSR J1839–3259.

## References

- [1] Abdo et al. 2009, *Science* 325, 845.
- [2] Abdo et al. 2009, *Science* 325, 848.
- [3] Abdo et al. 2010, *A&A* 524, 75.
- [4] Abdo et al. 2010, *ApJS* 187, 460.
- [5] Abdo et al. 2011 (arXiv:1108.1435)
- [6] Atwood et al. 2009, *ApJ* 697, 1071.
- [7] Camilo & Rasio 2005, *ASP Conf. Series* 328, 147.
- [8] Cordes & Lazio 2002 (arXiv:astro-ph/0207156)
- [9] Freire et al., submitted.
- [10] Harris 1996, *AJ* 112, 1487.
- [11] Heinke 2004, PhDT.
- [12] Kong et al. 2010, *ApJ* 723, 1219.
- [13] Kramer & Lorimer 2005, *Handbook of Pulsar Astronomy*.
- [14] Maxwell et al. 2007, *AAS* 211, 03.16
- [15] Ransom 2001, PhDT.
- [16] Ransom 2003, *ApJ* 589, 911.
- [17] Ransom 2007, *IAU Symposium* 246, 291.
- [18] Ransom et al. 2011, *ApJ* 727, 16.
- [19] Tam et al. 2011, *ApJ* 729, 90.
- [20] Venter et al. 2009, *ApJ* 696, 52.